Weed management and woodland creation – an evidence review of herbicide alternatives and impacts on biodiversity

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Abstract

1. Weed control is important for ensuring the rapid and successful establishment of trees in woodland creation projects. Over recent decades, herbicides have fulfilled this role across the forestry and conservation sectors because they are cost-effective, practical and have high efficacy. Glyphosate is currently widely used for this purpose. However, there are questions regarding the impact of herbicides on human and environmental health, prompting research into alternatives.

2. This evidence review assesses the effectiveness of a range of alternative weed control methods for woodland creation. The impact of weed control methods on the biodiversity value of created woodlands is also discussed.

3. *Review findings*: mulching can be as effective for promoting tree growth if the material used is sufficiently durable to last throughout the establishment period. Traditional black plastic is the most durable option but has clear environmental drawbacks. Biodegradable mulches, such as a straw and woodchips, show some promise but more research is needed to establish their utility. Mechanical weeding can have specific use on a site-by-site basis but cannot continue beyond the establishment phase. Mowing is ineffective in reducing root competition but has benefits when used in combination with other methods. Natural Herbicides (e.g. bilanafos) have a limited evidence base. Cover crops - particularly grass/wildflower mixes - have potential in former agricultural sites, especially in combination with soil inversion. Direct seeding also has significant weed control potential, producing a dense competitive canopy but also increasing establishment variability. The option of no weed aftercare increases the likelihood of competition and may enhance the sensitivity of seedlings to abiotic stress such as drought.

4. *Recommendations for future research*: Research gaps were identified on the efficacy of biodegradable mulches, soil inversion and direct seeding methods. The longer-term impact of glyphosate and other methods on biodiversity in newly created woodland is also an evidence gap.

1. Introduction

Vegetation immediately surrounding a newly planted tree competes with the young tree for water and nutrients. As the tree has yet to develop an extensive root system, initial growth can be severely reduced by this competition which can, in some cases, lead to the death of trees (Davies, 1985). In addition, tall vegetation can become wet and heavy in the autumn, collapsing onto and smothering small trees (Hart, 1991). Another problem is the interaction between the vegetation surrounding a new tree, and the likelihood of small mammal damage to new trees, with dense grass providing ideal cover for field voles (*Microtus agrestis).* In contrast, bare ground is not readily crossed by voles (Davies & Pepper, 1993).

Conventional forestry guidance is that some form of weed control is necessary for reliably establishing trees and promoting rapid growth (Willoughby et al. 2004a). Lowland broadleaved plantings often require weeding during the early part of the growth season, for up to 5 years after planting (Hart, 1991). For several decades, chemical control using herbicides has been the most widely recommended and used method in commercial forestry (Hart, 1991), and this idea of best practice for tree establishment has been adopted into conservation tree planting (Sharkey, personal communication, 2020). However, in recent years, the impact of herbicides on human and environmental health has become a concern (e.g. Van Bruggen et al. 2018), prompting research into alternatives. This review assesses the evidence surrounding the effectiveness of alternative weed control methods for establishing UK native trees with the aim of informing guidance on how to create native woodlands with high conservation value. We also investigate the potential impact of glyphosate and alternative methods on the biodiversity value of created woodlands.

2. Methodology

This review was conducted using Collaboration for Conservation Evidence's recommended guidelines for evidence synthesis (CCE, 2018). Literature for inclusion in this review was obtained via the following methods. Search engines Microsoft Academic, Google Scholar, Google, and BASE were used to find relevant literature using a search string with "glyphosate OR herbicide" AND the alternative intervention, AND "tree". Variations on the string using the alternative terms "tree planting", "tree establishment" and "woodland creation" were additionally searched to reduce the chance of missing relevant literature. The scientific name of each UK native tree species was searched in a string with glyphosate, such as "glyphosate AND *Betula pendula*". Reference lists were checked to identify additional studies and included where relevant. Only papers that referred to newly planted trees of species native to the UK were included for review, and studies from a UK context were preferred. However, to extend the number of suitable studies, those carried out in a non-UK setting were included providing their study tree species was also native to the UK. These were largely restricted to European studies. Where evidence is from outside the UK, this is identified in the text. Evidence produced in commercial forestry contexts as well from conservation/amenity tree planting was included on the condition at least some of the study species were native to the UK. A range of evidence sources were included, such as primary experimental studies, literature reviews, grey literature, unpublished field trials etc. Literature was not filtered by date. To obtain knowledge and expertise from Woodland Trust staff and external experts, a request for evidence was sent out via email to a stakeholder list. Informal interviews were conducted.

3. Results

3.1. Mulching

Mulching is the practice of supressing weed growth in the area immediately around the tree by placing some form of physical barrier onto the ground. This barrier can be made of various organic or synthetic materials. There is an extensive evidence base from many trials comparing various mulching materials with herbicide use and other non-herbicide methods of weed control.

3.1.1. Natural mulch materials

A trial at the Fordham Hall Woodland Trust estate (Essex), compared various mulches against an unweeded control plot in newly establishing broadleaf plots (Blakesley, 2007). Fleece mulch and plastic mulch performed much better than the unweeded control. In addition, straw mulch was more effective than other mulches for facilitating tree growth. However, due to field conditions, a trial with sufficient replication is needed to validate these results. The exact method of applying straw is also important, as experience from this trial indicated the straw treatment requires applying a large amount of straw in rigid bales in order to be effective. Using a thin covering of loose straw which is easily disturbed is very unlikely to replicate these results. After 4 growth seasons, saplings in straw treatment plots had started to come into direct competition with invading grasses, but there were no visible impacts on their establishment. A resurvey of this site, presently 15 years post establishment, would help to shed light on whether there was a longer-term impact of grass competition.

Straw has also shown some potential in the Czech Republic, on a range of broadleaved woody species also native to the UK (Dostálek et al. 2007). In a habitat restoration project, Dostálek et al. (2007) found mulching with straw to a depth of ~30cm was the most effective method for promoting tree growth over 5 years when compared with bark and fleece mulch and the unmulched control. Seedling growth was 2 and 3 times faster under the straw treatment when compared to bark and fleece bark respectively. The impact of mulching was determined for 318 trees/shrubs in each treatment; however, an important difference in mulch application is likely to have influenced the outcome. The bark and textile mulches were applied to a grass sward, in rows only 0.4m in width, whereas the straw mulch covered the entire plot. The small width of the rows of fleece and bark mulch will have impacted their success, as a 1.2m width is considered the minimum required area for effective weed suppression (Willoughby et al., 2004a). In addition, a herbicide treatment was not included in this experiment, making an overall summary of weed control efficacy difficult. However, in combination with Blakesley (2007), this suggests straw mulch is a promising technique worthy of further investigation with a controlled experimental design and herbicide treatments included. Future work on this method should also consider testing across a range of sites with more challenging conditions. For example, on an exposed site the method may be ineffective due to straw blowing away. The use of straw mulch may also present cost-effective or logistical challenges, affect the nutritional profile of soil, increase grazing damage and create a target for arsonists (Sharkey, personal communication 2020).

Across four American apple orchards, a spray-on mulch made of recycled newspaper fibre slurry provided improved tree growth during the 4-year establishment phase, compared to standard glyphosate application (Cline et al., 2011). Note that the slurry required the addition of a source of long fiber such as chopped cereal or flax straw, to provide a durable barrier upon drying. In contrast, wastepaper slurry mulch did not promote tree growth in a Scots pine plantation in southern Finland over 4 years, being outperformed by glyphosate. This can be explained by the small diameter of the mulch area ($60cm^2$) and a lack of durability of the fibre mulch in some plots. The texture of the paper fibre mulch impacted its durability; coarser textured mulches lasted well over two years, while finely shredded mixtures degraded (Siipilehto & Lyly, 1995). Silver birch planted on an ex-arable field in Finland grew best over the first two years when weeded with a range of different herbicides, but glyphosate, was no more effective at promoting growth than a wooden particle board mulch (Ferm et al., 1994). However, the mulch had the disadvantage of increasing tree damage by voles by providing shelter for them. Three $100m^2$ planting blocks were tested per treatment with a planting density of 2000 trees ha^{-1} (Ferm et al., 1994).

At an English farm woodland site, most biodegradable mulch materials were ineffective for improving growth, with the exception of coir mats with photodegradable membrane backing (Stokes, 2012). Ten different mulches were applied, with 64 trees per treatment each. Although the coir mats were not as effective as herbicide for promoting growth, they performed well enough to be considered a useful, practical, cost-effective alternative (Stokes, 2012). Mulch of various kinds increased growth of a wide variety of UK native tree species planted in pastures in a large study across two sites in Belgium (Samyn & De Vos, 2002). Ecopla (a sheet mulch composed of paper mill sludge, compost and old paper) was effective for promoting the growth rate of oak and alder but also increased vole damage. Here, coir mats also performed well and proved more durable than Ecopla. There was a strong relationship between the diameter of mulch area and growth rate, highlighting the importance of mulching a sufficient area in addition to choosing a suitable material (Samyn & De Vos, 2002). It is noted that woodchip/bark mulch is used extensively in the horticultural sector. The UK forestry sector produces these products, and woodchip is readily and cheaply available to many landowners. However, it does not seem to have been widely and rigorously tested as a potential mulch within UK woodland creation projects and perhaps needs to be explored further (Sharkey, personal communication, 2020).

3.1.2. Synthetic mulch materials

A range of synthetic mulch materials have been trialled by Davies (1988a, 1988b) for their effectiveness as mulches in the UK, producing the following key findings:

- Mulch sheet material should be opaque and non-permeable.
- Mulch materials should remain robust for 3 years.

- Mulch sheets require a minimum thickness to resist weather, animal activity, thorns and stone damage and prevent weeds growing through.
- Corners of the sheeting should be buried and weighted down (e.g. via earth clods).
- It is sometimes necessary to remove vegetation before applying the mulch sheet, including via chemical herbicide.
- Sheet mulches have potential to increase grazing damage by proving a sheltered nesting place for voles. Davies (1998a) suggests weighting mulch sheets down can resist this, but plastic vole guards may also be necessary.
- Mulches must cover at least $1m^2$ around the base of each tree to be effective. However, Willoughby et al. (2004a) recommend a $1.2m^2$ application area.
- Weed competition is highest in the spring and early summer, so mulch sheets must be applied before this period (Samyn & De Vos, 2002).

A 1m wide plastic mulch band performed better than the standard forestry treatment of 1m herbicide bands when the survival and growth of planted ash saplings was assessed across two lowland ex-agricultural sites in the UK (Willoughby, 1999). Indeed, plastic is often preferred as a mulch sheet material because of its durability and cheaper cost compared to other materials (Davies, 1988a). However, due to the risk of persistent microplastic pollution, it is not necessarily a more environmentally sound option than herbicide. A biodegradable bioplastic mulch sheet has been tested in a 4-year study in Spain, on walnut trees (Coello et al., 2017) but only a third of the 72 bioplastic sheets remained intact for the study period, proving less durable than traditional plastic sheet mulch or a woodchip mulch. The poor durability of biodegradable membranes is consistent with findings from a UK experiment (Stokes, 2012). However, in this case, the combination of a $1.2m^2$ coir mat with a photodegradable plastic membrane backing was sufficiently durable to be effective at promoting tree growth. Longer term trials in a range of climatic conditions are required to fully assess whether bioplastics hold potential, as they have not yet proven sufficiently durable.

3.1.3. Environmental drawbacks of mulching

There are some potential environmental impacts of mulch materials which need consideration. Inorganic mulches can form a source of solid chemical waste in the environment. Unless fully biodegradable, they will need to be collected at the end of their useful life. Unless inert, waste materials used as mulches may also emit pollutants onto a site. Organic mulches with a high C:N ratio, such as bark, wood chips and straw, can induce N deficiency in mulched trees and nitrogenous fertiliser may be needed to counteract this (Willoughby et al., 2004).

3.2. Manual/mechanical weeding

Prior to planting, sites can be prepared by soil cultivation, which uproots and buries weeds. The effectiveness of cultivation for weed control depends on the site type. On infertile upland soils, cultivation can offer sufficient weed control to allow tree establishment, often with no further intervention. However, on lowland fertile sites, such as brown earths, cultivation can also facilitate weed establishment and growth (Willoughby et al., 2004a).

Once trees are planted, mechanical control becomes less practical. Hart (1991) describes manual/mechanical weeding as expensive, labour intensive, and ineffective at fully removing competition. In addition, there is a high risk of accidental damage to trees in the process. This method is also unsuited on steep sites as machinery access can be difficult. Few weeding trials appear to have included a mechanical control method as a treatment, probably because of the practical difficulties involved. With the exception of ploughing, scarification and one-off mounding (elevated planting spots), the practicality of repeated mechanical control have prevented it from being considered as an alternative weed control method, although recent development in hand-held equipment could be the focus of future research. However, the following studies do address mechanical weed control techniques.

An experiment from the 1920s-30s period presented by Davies (1985) showed hoeing had some benefits for tree growth, but this was only compared with cutting weeds above the ground, which further evidence has shown to be highly ineffective. Work from Sweden investigated mounding as an alternative to herbicide use for establishing pedunculate oak (Bolte & Löf, 2010). Although a combination of mounding and herbicide gave the biggest boost to root growth, the individual treatments were similarly effective at increasing root biomass compared to no intervention, suggesting mounding is a suitable alternative method. Mounding is usually used in northern and upland regions where low soil temperature and high water table can cause problems for tree establishment, and could be suitable for specific locations of the UK.

Potential impacts of cultivation include soil erosion and run-off, nitrification, acidification, oxidisation of organic material, and disruption of complex soil ecosystems. The worst effects are likely to be associated with deep plough while less intensive techniques such as scarification and mounding pose fewer risks (Willoughby et al., 2004a).

3.3. Mowing

A review summarising the results of 7 classic planting experiments illustrates that competition for moisture and nutrients is the key mechanism by which weeds supress sapling growth (Davies, 1985). The experiments demonstrate that cultivation, herbicides or mulching can all impact the roots of weeds, but that mowing/cutting weeds above the ground is not effective. Although not comparable with the other control methods, cutting vegetation at the base of a tree can prevent tall, dense vegetation collapsing onto and crushing small saplings when wet (Hart, 1991), and mowing of the grass between the weed free areas can help reduce new seeding into the weed free areas (Willoughby et al., 2004a). This is recommended best practice for woodland creation, along with the establishment of a less competitive ground cover (grass, or grass-wildflower mix) between the weeded lines of trees. Potential negative environmental impacts of repeated mowing with mechanised cutters can include soil compaction, air pollution from exhaust gases, and the risk of soil and water pollution from spillage of fuels and lubricants (Willoughby et al., 2004a).

3.4. Natural Herbicides

Two natural substances - bilanafos and citronella oil - were found to be effective as alternative herbicides and of potential use for tree establishment, when compared with a traditional herbicide (Clay et al., 2005). However, this does not preclude the possibility of unintended effects on non-target species. Green (2003) review the potential of bioherbicides for control of major weed species in forestry. This approach involves inoculating weeds with a native pathogen (such as a fungus) for control. However, this is not an option for general spot treatment of weeds around tree bases, as it must be specifically targeted at a particular weed species. It has most promise for preventing the regrowth of rhododendron stumps.

3.5. Soil inversion and cover crops

Cover crops are generally ineffective at supressing weeds and promoting tree growth (Willoughby, 1999), unless combined with 1.2m wide vegetation free areas around the trees (Willoughby, personal communication, 2020). This suggests that cover crops have potential for use in combination with mulching as part of an integrated approach to weed management at appropriate sites. The potential for increased vole damage under cover crops is a disadvantage. For example, a clover ground cover was favoured by voles over mulch and herbicide treatments leading to half of saplings incurring vole damage under this treatment in a Finnish study on silver birch (Ferm et al., 1994).

Willoughby (1999) attempted to establish a cover crop on fertile agricultural soils and describes the inevitable problem of high fertility soil leading to competitive weed species such as grasses dominating the intended ground cover species. With the aim of overcoming this issue, Landlife (2008) have trialled a novel ground preparation technique called soil inversion at 35 sites across the UK. The results have not yet been published in a peer-review journal. A specialist plough is used to flip the top 1m of soil, so that the fertile topsoil is buried, and the infertile subsoil brought to the surface to form the new planting medium. The site is then sown with a grass-free mix of uncompetitive native wildflowers, including grassland perennials and cornfield annuals which act as a first-year ground cover. Problematic weed seeds present in the topsoil layer are buried at depth, mostly preventing their germination, and the seed-free, low fertility subsoil is less readily colonised by new weeds, meaning the sowing of a grass cover (the usual forestry practice which then competes strongly with trees) is not necessary. Nutrient levels in the surface soil after soil inversion were significantly reduced for at least the 5-year study period (Glen et al., 2017). Where soil inversion and wildflower ground cover has been used, tree growth on light soils has been up to 3 times faster than in traditional forestry site prep with herbicides, and tree mortality greatly reduced (Landlife, 2008). There is also a suggestion that trees established on soil inversion sites have shown increased resilience to drought. These proposed benefits (increased growth, increased survival, and increased drought resistance) need rigorous, objective testing in replicated and controlled field experiments on all types of soil, before the technique could be recommended more widely. Indeed, Landlife (2008), suggest application of glyphosate may be required prior to sowing to clear vegetation. There are also serious potential soil carbon emission implications of deep ploughing, and practical limitations in sites with heavy soils.

3.6. Direct seeding

Direct seeding is an alternative method of woodland creation which aims to aid natural regeneration by artificially introducing tree seed to a site. The evidence for direct seeding in UK woodland is limited compared with what is known about planting. The most comprehensive guidance on direct seeding for broadleaved woodland creation to date is provided in Willoughby et al. (2004b). This guidance reports that direct seeding can be successful in certain situations, and recommends appropriate silvicultural techniques, but warns the outcome is less predictable compared with planting trees. Oak, ash, sycamore, wild cherry, field maple and birch are recommended as suitable species by Willoughby et al. (2004b) and this list has since extended to rowan, alder, sweet chestnut and a wide variety of native shrub species (Willoughby and Jinks, 2009). A breakdown of the price of direct seeding compared with planting is also provided in Willoughby et al. (2004b).
Direct seeding is recommended by Willoughby et al. (2004b) for creating new broadleaved woodland on well-drained lowland sites with low populations of seed predators; for example, improved grassland or arable sites, or well-restored brownfield. Recent work has also demonstrated success with direct seeding for re-stocking clear-felled upland sites with broadleaves, even with significant numbers of seed predators known to be present (Willoughby et al., 2019). On fertile soils, there may be prolific weed growth alongside the germination of the tree seedlings. To ensure establishment, effective weed control is essential (Willoughby et al., 2004b). The authors recommend the use of herbicides to maintain 80–90% of the site weed free until trees have become established.

Although direct seeding as a method of tree establishment generally requires the use of herbicide, Willoughby et al. (2004b) suggest the method does have potential to reduce herbicide use compared with traditional planting. Most obviously, direct seeding eliminates the need for herbicide usage during nursery production, as this stage is removed altogether. In the field, direct seeding can produce high seedling densities without transplant shock, resulting in much earlier canopy closure (3–5 years after sowing) compared with traditional transplanting at a wider spacing (which may take 10 or more years, depending on spacing). Early canopy closure reduces the length of time herbicides may need to be used, by creating shady ground conditions sooner. For example, in some Forestry Commission experiments on very fertile weedy sites, weed control was only required for the first two years after sowing because of early canopy closure, compared with a further 1–2 years of herbicide application required for transplants (Willoughby et al., 2004b).

Despite the requirement for more extensive chemical control, as opposed to the usual practice of band/spot sprays for planted trees, Willoughby et al. (2004b) still consider the faster canopy closure will lead to an overall reduction in herbicide use. A later study, focussing in more detail on the optimum number of years of weed management for direct seeding, backs up this suggestion (Willoughby and Jinks, 2009). The key finding was that weeding with herbicides for one year after sowing gave a significant benefit to overall survival (+35%), but that weeding for a maximum of three years gave the most improvement to survival and growth (a further +25%). Beyond three years, there was no benefit from weeding, because the trees had already formed a canopy and were shading out the competing vegetation. Willoughby & Jinks (2009) used eight native or naturalised broadleaf species, on fertile lowland ex-agricultural sites. After sowing, plots were chemically weeded for either one, two, three or four years. Control plots received no herbicide treatment after sowing but did receive an initial application of glyphosate to kill existing vegetation prior to cultivation. Interestingly, by the end of the fourth year, around 15,000 stems ha^{-1} had established in the control plots, which is several times the usual density achieved by planting. However, because of the pre-cultivation glyphosate application it is not possible to conclude whether an acceptable density of trees could have been achieved without it. Future research is needed to clarify this.

On fertile sites, direct seeding with an overall pre-cultivation glyphosate treatment plus one year of post-sowing treatment, could be roughly comparable (in terms of quantity of herbicide usage) with planting at standard density and spot weeding for 4 years (Willoughby and Jinks, 2009). However, the result of 15,000 stems ha^{-1} with only the pre-cultivation treatment suggests this is also a realistic option on fertile lowland sites, and therefore highlights the potential for direct seeding to accommodate substantial reductions in herbicide input. On less fertile upland sites, direct seeding has been shown to be a successful method for converting clear-felled commercial conifer forests to native woodland (Willoughby et al., 2019). This experiment was not designed to test the effects of weed management, but a successful outcome of 9000-12,000 seedlings ha^{-1} was achieved after seven years, using a single initial overall application of glyphosate. The initial treatment was considered necessary due to a 6-year fallow period after clear felling, during which the site had become colonised with grass. However, on similar, low fertility upland sites (e.g. sites with an Ecological Site Classification soil nutrient regime of 'poor' or 'very poor'), if sowing takes place within 6–12 months of clearing, chemical weeding may not always be necessary, and pre-sowing cultivation could be sufficient to control weeds. Other key lessons from Willoughby et al. (2019) are that direct seeding significantly improved seedling recruitment compared to natural regeneration in cultivated unsown control plots, with the unsown plots producing 650-1700 seedlings ha^{-1}. Cultivation and sowing rate are also very important for promoting seedling establishment. Minimum recommended sowing rates for various tree species are provided in Willoughby et al. (2004b) and in Willoughby et al. (2019). For direct seeding to achieve rapid creation of woodland, and thereby suppress competing vegetation, Willoughby et al. (2019) recommend aiming to establish a minimum of 10,000 ha^{-1} by sowing as much viable seed as possible.

These recent findings have inspired a trial at a 35 hectare plantation on ancient woodland site (PAWS) in Ceredigion, Wales, which the Woodland Trust is involved with restoring to broadleaved woodland. Sowing took place in November 2019 on an area recently clear-felled of conifers. At the time of writing, it is too early to assess the results, but the aim of the trial is to build on the work by Willoughby et al. (2019) by experimentally applying direct seeding on steep, low fertility, recently clear-felled upland sites. The trial will test various cultivation techniques and be compared with areas allowed to naturally regenerate. As this is a PAWS, it is assumed herbicide will not be used due to the sensitivity of the habitat. This will test the hypothesis that low fertility upland sites seeded immediately after clear-felling of conifers may not require any chemical weed control for successful broadleaved tree establishment via direct seeding (Willoughby et al. 2019).

Direct seeding has been trialled at the Woodland Trust's Comfort's Wood site in Kent. An ex-arable plot was direct seeded in 1991 alongside a conventionally planted area (Tucker, personal communication, 2020). After 12 years, the direct seeded area had developed into dense woodland dominated by oak with a shrub understorey and a random, natural appearance. Stocking and form are very good (2-5 trees/m^2 and 5-6m tall respectively). Survival rates for individual species sown are not presented, but the direct seeding has led to a greater degree of canopy closure than the conventional planted area, aligning well with Willoughby et al. (2004b). However, immediately after sowing, couch grass developed and appeared to slow the development of tree seedlings, and both the sown area and the traditionally planted area were treated with a herbicide during the first winter. No further application of herbicide was performed, suggesting on a lowland ex-arable site, a single dose may be sufficient to allow adequate tree seedling establishment, supporting the findings of Willoughby et al. (2009).

A direct seeding trial was also set up very recently on a plantation on an ancient woodland site (PAWS) in North Yorkshire, with the aim of replacing an area of felled conifers with native trees (Feather, personal communication, 2020). Chemical weeding was not an option on this site due to the sensitive nature of the habitat, so it was hoped that the reduced weed competition due to trampling of vegetation and disturbed ground immediately following the felling operation would be sufficient to allow the seedlings to establish. Extreme spring drought led to extremely poor germination in the first year, highlighting the unpredictability of the method as warned by Willoughby et al. (2004b). Consequently, this case study is currently unable to provide any evidence as to whether direct seeding with zero herbicide input can be successful for restoring native trees on PAWS. However, some seed may have remained dormant and could germinate next spring; therefore future monitoring of this site will provide insight as to the resilience of low input methods to spring drought. Some of the germination failure in this trial was possibly due to lack of soil cultivation or seed scarification (Willoughby et al. 2019). This is a constraint of working on sensitive soils such as those found on ancient woodland sites, which possibly hinders the ability to achieve full establishment potential. However, light raking after sowing to help incorporate the seed, may be an option (Feather, personal communication, 2020).

The sowing of cover crops in combination with direct seeding has been proposed as a method of further reducing herbicide inputs. The combination of direct seeding trees with an arable crop is termed Temperate Taungya and was proposed over 25 years ago with claims that the cover crop would afford protection to the growing seedlings and suppress weeds, reducing the need for herbicide (Watson, 1994). Subsequently, a well replicated, peer-reviewed experiment in the UK lowlands concluded that arable cover crops are not sufficient to replace chemical weed control, and any benefit offered is outweighed by the competition between the crop and the trees (Willoughby et al., 2004c).

An alternative cover crop of no-grass wildflower mix, in combination with deep-plough soil inversion, was trialled for a directly seeded Woodland Trust site in Derbyshire (Porter, personal communication, 2020). The results for oak and cherry establishment were very successful. Some birch also established, but ash and field maple failed. It has been demonstrated elsewhere that field maple and ash can establish via direct seeding (Willoughby and Jinks, 2009), so it is not clear why these species failed on this occasion. To what degree the wildflower cover crop afforded protection or suppression to the trees is unknown, as the experiment did not have control plots. The area is reported to have remained free from colonising weeds in the first few years; however the wildflower cover crop itself appeared to "swamp" the tree seedlings, suggesting they may have been suppressed by it (Porter, personal communication, 2020) similar to the finding with arable cover crops (Willoughby et al. 2004c). No estimate of the resulting density of trees is available for this case study, but a qualitative assessment of the results after 13 years suggests tree establishment has not been as successful as adjacent traditional planting, in either quantity or size. However, the biodiversity benefits are apparent, with diverse structure due to random spacing of trees, open areas with wildflowers as well as natural colonisation of heathland species such as gorse (Logan, personal communication, 2020). Prior to soil inversion, the existing vegetation (arable and pasture) on the 10ha site was killed using glyphosate at the standard dose of 5 lts/ha of glyphosate, thus a total of 50l was used for the whole area. This is lower than the estimated requirement (78.7l) for repeated 1m spot applications over 3 years if the area had been planted traditionally at a density of 2250 trees/ha^{-1}. This estimate is based on seven spot applications at the standard concentration (Porter, personal communication 2020). There was no subsequent herbicide treatment after the soil inversion took place. The observed success at this site in terms of biodiversity demonstrates that the objectives of conservation woodland can be achieved using a reduced quantity of herbicide in a single application prior to soil inversion and sowing of a wildflower cover crop. The soil-inversion was considered sufficient to remove weeds by burying them at depth prior to sowing (Porter, personal communication, 2020); however, trials with unsprayed and uncultivated control plots are needed to verify this.

Overall, the available evidence suggests direct seeding can be an effective means of creating native woodland in both upland and lowland areas, with potential to provide meaningful reductions in herbicide input, although unlikely to reduce to zero in most scenarios. Currently, a constraint to the use of direct seeding for native woodland creation in the UK is the lack of robust and contemporary evidence from the UK for its application. However, this is expected to be addressed in the coming years as more trial sites are established and improved techniques are developed for sowing and seed treatment (Waterson, personal communication, 2020).

3.7. No aftercare

The majority of weed control trials have measured sapling survival (%) and some measure of growth rate. A common pattern has emerged from these experiments; while weed control is important for promoting sapling growth, it often has a very minor impact on survival rates. This is evidenced by many studies which have reported comparable survival between treatments and in unweeded control plots. For example, in Finland, Siipilehto & Lyly (1995) found high survival of planted Scots pine, on average 90%, with no significant effect between the control plot, mulch, or herbicides over 3 years. For beech, oak, wild cherry and hawthorn across 3 study sites in Denmark and southern Sweden, the effect of weed control on seedling survival was minor, but there was a strong effect on seedling growth (Löf et al., 2004).

The effect of spot herbicide treatments was assessed after 2 years for the establishment of oak and sycamore transplants in the UK (Davies, 1985) and the effect of herbicide was not significant for oak survival with 91-97% surviving in the unweeded plots (n=128). Weeding improved the survival of sycamore in this trial, but unweeded controls still had relatively high survival (81%; n=128). Similarly, survival of ash was very high after 3 years in all of the different treatments compared by Willoughby (1999) across two sites in the UK; the lowest survival percentage was 94% in winter barley ground cover. The control had a survival rate of 100% (n=60) at one of the experimental sites, and 98% (n=72) at the other site. Furthermore, in the unpublished Woodland Trust trial at Fordham Hall, the untreated control had a survival rate of 89% (n=64), but the mulches all increased survival compared to the control (99% survival for plastic (n=71), 100% survival for fleece (n=72) and 100% for straw (n=18)). While sapling survival may be largely unaffected by direct weed competition, additional stressors such as an increased severity of drought events may require earlier and ongoing intervention.

3.8. Impacts of weed management on biodiversity of created woodlands

3.8.1. Effects of glyphosate on biodiversity of the resulting woodland

The latest European Union renewal report on glyphosate (European Commission, 2017) concluded that under the proposed and supported conditions of use, glyphosate has no unacceptable effects on the environment, including consideration of its impact on biodiversity and the ecosystem. This conclusion is based on a comprehensive review of the evidence at that time and is the most complete safety assessment available. However, the EU recommends minimising or avoiding the use of all herbicides in certain places, such as school grounds and certain protected conservation areas.

In small-scale experiments, some impacts of glyphosate have been observed, which may be of interest for woodland creation. In greenhouse conditions, glyphosate has been shown to reduce earthworm activity and decrease the ability of plant roots to form associations with arbuscular mycorrhizal fungi - two important aspects of soil ecosystem function (Zaller et al., 2015). However, the study could only reveal short term influences of glyphosate, and the findings may not be applicable to field conditions. In an outdoor container experiment in Finland, glyphosate was also shown to have a negative effect on beneficial mycorrhizal fungi in non-target grasses, planted in the following growing season after a season of glyphosate application (Helander et al., 2018). However, this finding is yet to be demonstrated in field conditions.

In contrast, a short-term field study in Australia on the impact of a range of herbicide actives on the diversity and abundance of soil bacteria and fungi did not find any major differences between a control mulch treatment and the herbicide treatments (Bottrill et al., 2020). It is important to note the field conditions were not comparable with the UK climate, and only short-term impacts could be revealed.

There is no evidence that the use of glyphosate for establishing trees has any impact on the long-term ecological functioning of planted woodlands, but subtle effects may never have been identified. Of particular interest would be research into whether glyphosate application reduces the ability of planted tree sapling roots to form mycorrhizal associations in a range of UK field conditions, and whether this impacts their future development.

Invertebrate abundance in UK field margins has been found to be negatively affected by the direct application of glyphosate at varying concentrations (360g-1440g/ha) (Haughton et al., 1999a). Spiders have been shown to be particularly susceptible in another experiment using lower concentrations (90 – 360g/ha). At 360g/ha, the abundance of spiders was consistently reduced, suggesting glyphosate drift at concentrations above this level is harmful for this invertebrate group (Haughton et al., 1999b).

Gove et al. (2007) studied the impact of glyphosate drift from agricultural fields on adjacent woodland and tested known agricultural drift-level concentrations of glyphosate on six species of plant typically found in UK ancient semi-natural woodland. In greenhouse and field tests, drift-level glyphosate applications caused increased mortality, decreased biomass and decreased fecundity of all species tested. Surveys of woodland edges bordering high, medium and low glyphosate input fields, revealed the abundance of the most sensitive woodland flora species was negatively correlated with the level of herbicide input on the adjacent fields. These effects were found at least 4m into the woodland edge, but not beyond 10m. A buffer zone of at least 5m is recommended to protect woodland flora. These findings are supported by Marrs et al. (1989) who found plants of conservation concern were affected by glyphosate drift up to 6m from the sprayer and recommends buffer areas of 5-10m between agricultural fields and conservation areas.

However, it is important to note that the use of glyphosate for woodland creation scenarios, in terms of dose and application rate, is much different to horticultural and agricultural situations where weeds pose an annual and adaptive threat. Weeding of trees is undertaken using handheld knapsack sprayers and is restricted to a 1m diameter around the tree. This allows for much more targeted treatments, and much lower volumes of use. Handheld applicators tend to lead to much lower risk of drift both in terms of extent and volumes. It should also be noted that in many cases, woodland creation is taking place on ex-arable/agricultural land, leading to a significant reduction in the herbicide/pesticide burden on such sites compared to its historical use. Weeding of trees also tends to be for a short period of 1-3 years, after which no further herbicide treatment is required.

The quantities of glyphosate used annually by the conservation and forestry sectors are likely to be miniscule compared to those used in agriculture, and as such the relative environmental and human risks are much lower. For context, it is estimated that a standard agricultural sprayer could spray the entire Woodland Trust Estate’s annual usage of glyphosate in less than a day of continuous working (Sharkey, personal communication, 2020). Spot sprays around young trees, on ex-agricultural land that has been subject to previous more intense spray regimes is unlikely to cause significant loss of biodiversity, and plants that will be affected are ones that are unlikely to survive around the base of the tree once it has started to produce a canopy (Kirby, personal communication, 2020).

3.8.2. Effects of alternative weeding methods on biodiversity of the resulting woodland

All weed management interventions have the potential to cause some non-desirable environmental impacts. This section is specifically concerned with any evidence that these methods have any effect on the biodiversity of the resulting woodland.

None of the weeding experiments published in peer-reviewed journals have recorded the biodiversity impact on the resulting woodland site, as this is not usually the focus of the research. Some unpublished anecdotal observations from case-studies are available, but these cannot provide robust evidence, and the observations are only presented for the first few years after the trees are planted, so there is no evidence for long term influence of weeding techniques. For example, Blakesley (2007) measured the species richness of the ground flora in experimental weeding plots and found the bare ground treatments (the mulches and soil inversion) had much higher species richness after 3 years than the sward plot (no aftercare). This is due to the colonisation of pioneering annual herbs, which are expected to be gradually replaced over time with grasses. Similarly, Landlife (2008) report anecdotal observations of increased initial biodiversity at soil inversion sites, resulting from the creation of low soil fertility conditions and the addition of diverse wildflower seed mixes. The sown ground cover supports pollinating insects in the short-term, and there were short-term observations of increases in some birds of conservation concern at some of the trial sites. What impact soil inversion and wildflower cover crops will have for woodland biodiversity in the long-term, is unknown. Overall, there is no evidence available to link any weeding technique used to establish trees, and the biodiversity outcome for the resulting established woodland.

4. Conclusion

Most research has been conducted into the effects of mulches, sometimes showing them to be as effective as herbicides for promoting tree growth. Mulches could therefore provide an option for moving away from reliance on herbicides in woodland creation on suitable sites. There is considerable evidence for the appropriate size of mulched area required to improve success, but more uncertainty surrounding the ideal material.

Manual weeding has practical constraints which means little research has been conducted into its effectiveness. Mowing alone has been shown to be ineffective as a means of weed control and should not be considered as a valid option. No aftercare post-sowing is a risky option; the evidence shows survival can be adequate, but growth will almost certainly be suppressed, prolonging the period a tree is vulnerable to browsing. Herbicide alternatives such as natural products are not necessarily any safer than traditional herbicides, and presently none appear suitable for weeding around planted trees. Cover crops directly seeded into fertile soil are not effective, but the combination of no-grass wildflower mixes with soil inversion shows some potential for certain soil types and flatter sites, but more rigorous research is needed into this method before it could be recommended widely.

Direct seeding has shown great potential to reduce overall herbicide use on a range of sites, providing the appropriate silvicultural guidance is followed. It encourages high density tree establishment and faster canopy closure, although tree establishment is less predictable as a result.

The extent to which various weed control methods, including the standard use of glyphosate, impact the long-term biodiversity value of newly established woodland ecosystems, represents an evidence gap. Utilising soil inversion and a wildflower cover crop would deliver a boost to initial floral diversity via the sowing of native wildflowers, potentially benefitting insects, birds and mammals in the short-term.

Presently, glyphosate remains both a legal and cost-effective weed control technique to aid woodland establishment and is seen as low risk in terms of environmental and human health impacts. However, it seems prudent, given the growing concerns around glyphosate, that alternative weed control techniques for woodland creation should be investigated.

Recommendations for future research include:

- More extensive, sufficiently replicated and carefully controlled trials of straw mulch, woodchip, paper slurry and bioplastic mulch sheeting in a range of UK conditions.
- Research into the soil carbon impacts of soil inversion over the short and long term.
- Further trials into the use of non-grass wildflower cover crops.
- Trials of soil inversion with and without the use of herbicides to provide initial whole site clearance of vegetation. Also, a comparison of the volume of glyphosate used for this form of site preparation compared with traditional spot spraying of saplings over the establishment period.
- Research into the short and long-term impacts of standard glyphosate spot spraying, compared to other weed control techniques on soil ecology, particularly to identify any impact on the formation of mycorrhizal relationships between beneficial soil fungi and sapling roots in field conditions.
- All trials into alternative weed control methods should include a measure of biodiversity outcomes over the long term to highlight any relationship between method of weed control and biodiversity of resulting woodland.
- Controlled and replicated trials combining soil inversion with direct seeding.

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6. Conflict of interest statement

The author declares no conflict of interest

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